Quantum and classical information processing with a single quantum dot in photonic crystal cavity

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Quantum dots (QDs) coupled to photonic crystal cavities are interesting both as a testbed for fundamental cavity quantum electrodynamics (CQED) experiments, as well as nano-scale devices for optical quantum and classical information processing. In addition to providing a scalable, robust, on-chip, semiconductor platform, this coupled system also enables very large dipole-field interaction strength, as a result of the field localization inside of sub-cubic wavelength volume (vacuum Rabi frequency is in the range of 10s of GHz). In this paper, we describe some of the recent experiments performed on this system in our group.

Interaction of QD with cavity mode happens in two different regimes: weak coupling, where the interaction strength is smaller than the energy loss from the system (cavity decay and QD spontaneous emission) and strong coupling, where the interaction strength is larger than the losses in the system. In the strong coupling regime, the QD and the cavity mode mix and result in polaritons, which is manifested as split cavity resonance at zero detuning of the QD and the cavity mode. Thus in a strongly coupled QD-cavity system, one can probe light-matter interaction at the most fundamental level.

The InAs QD sample is grown by molecular beam epitaxy. Photonic crystal cavities are then made by e-beam lithography, followed by reactive ion etching and removal of AlGaAs sacrificial layer by HF. The chip is kept at cryogenic temperatures (4K to 50K) in a helium-flow cryostat. All the optical experiments are performed in a cross-polarized reflectivity setup. The setup along with SEM picture of a fabricated cavity and electric field profile of the cavity mode is shown in Fig. 1.

We have resonantly probed a strongly coupled QD-cavity system (1) and observed the split resonance (as shown in Fig. 2). The enhanced light-matter interaction in this system enables ultra-low control power electro-optic modulation as a coupled single QD can modify the cavity transmission spectrum. The QD resonance frequency was modulated by a lateral electric field via quantum confined Stark effect (2), and thus the optical transmission through the cavity was changed. Fig. 3(a) shows the different cavity transmission spectra for different lateral bias applied and Fig. 3(b) shows the temporal modulation of the optical signal by an electrical signal. A modulation speed of 150MHz was demonstrated with estimated control energy of 1fJ/bit. Currently the modulation speed is limited by the RC constant of the transmission line and the cryostat, while the device-limited speed is in tens of GHz (3).

We have also investigated the quantum nature of this system by probing the photon blockade (4). The presence of the QD makes the otherwise linear cavity, nonlinear, and coupling of one photon to the system hinders the coupling of the second photon. This phenomenon is called photon blockade and can be used to produce deterministic single photons at the output of the cavity QED system (5).

One of the puzzling aspects of the solid state cavity quantum electro-dynamics experiments with QD is off-resonant QD-cavity coupling. Unlike atomic systems, the QD couples to the cavity even when they are far-detuned. We have studied this effect by resonant excitation of the QD (6). We have shown that this coupling can be used for resonant QD spectroscopy. We have also shown that when the cavity is resonantly excited, emission from the QD is observed. Fig. 4 shows experimental results on the off-resonant coupling between the QD and the cavity. By observing the cavity and QD emission one can estimate the QD and the cavity linewidth respectively [Fig. 4 (c)]. We have performed similar experiments on several QD-cavity systems with different detunings between them and have measured the QD linewidth as a function of the excitation laser power. We found that the QD linewidth has a constant power-independent broadening, which is larger than the theoretical prediction (7). This indicates that the additional broadening has to be a result of the mechanism that facilitates off-resonant interaction between the QD and the cavity.

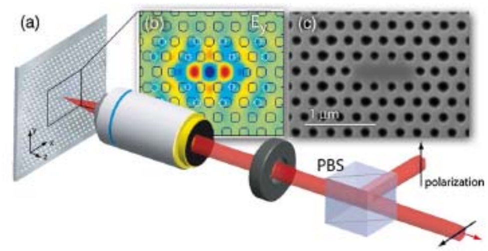

Fig. 1: (a) Cross-polarized reflectivity setup; (b) The FDTD simulation of the electric field profile of the cavity mode; (c) SEM image of the fabricated cavity.

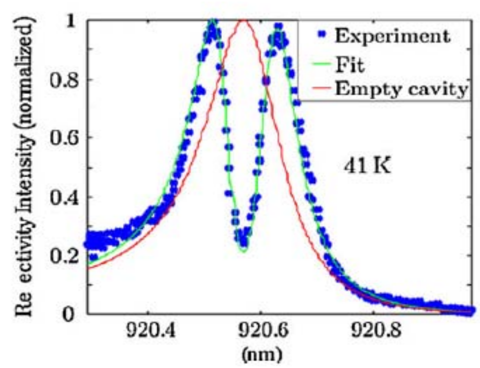

Fig. 2: Transmission spectrum of a strongly coupled QD-cavity system.

In conclusion, the experiments show that the coupled QD-cavity system is a promising candidate for probing CQED as well as for optical information processing. Our present work includes building of a three level system in a QD coupled to cavity, which is essential for construction of any quantum information processing devices.

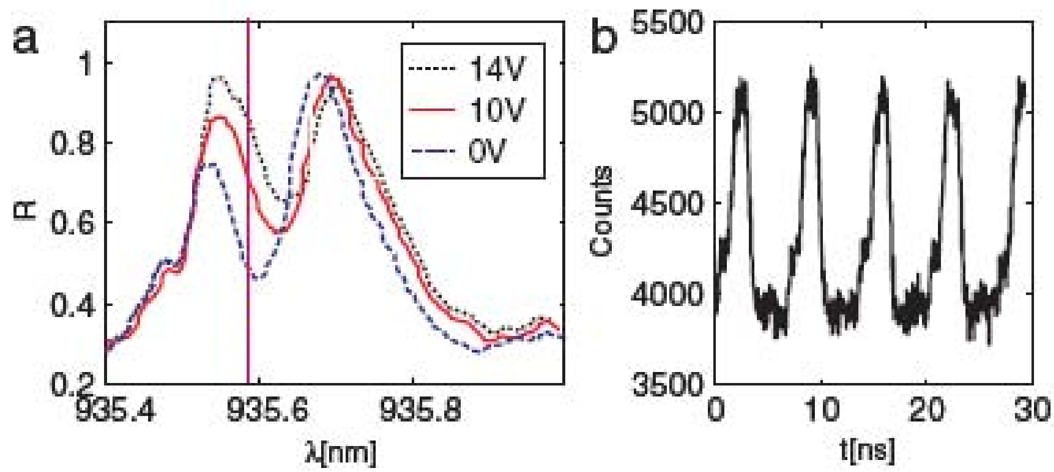

Fig. 3: (a) Transmission spectra of the cavity with different lateral bias voltage across the QD. (b) The modulated optical signal with time. A modulation speed of 150MHz is experimentally achieved.

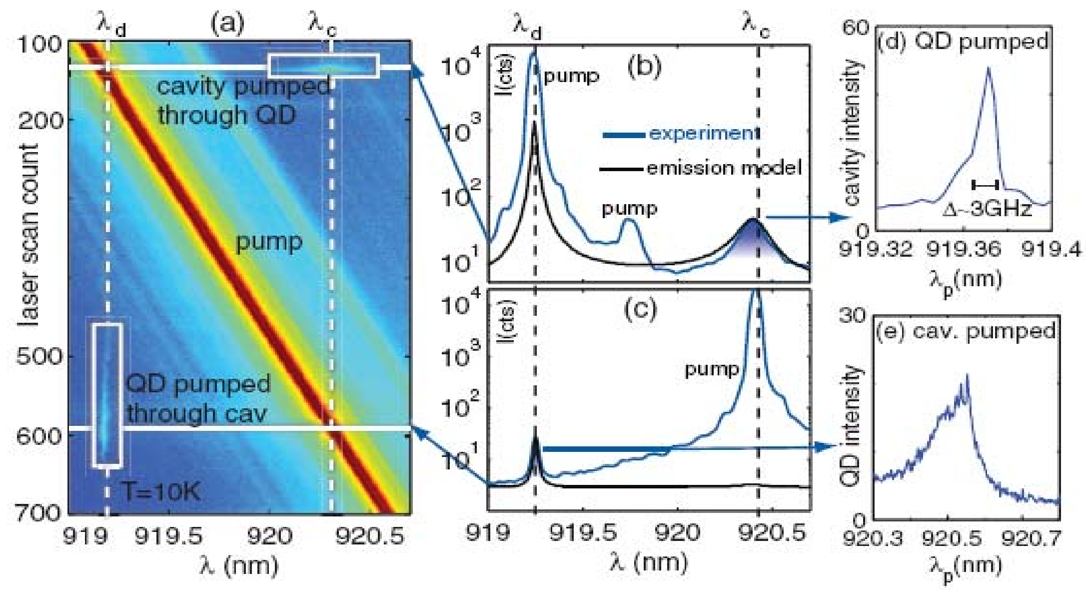

Fig. 4: (a) Two-dimensional plot of the laser scanning the coupled QD-cavity system in time (laser scan count is proportional to time). (b) Spectra showing the off-resonant coupling between the QD and the cavity mode. When the laser is resonant with the QD, we observe emission from the cavity mode. Similarly, laser resonant with the cavity mode causes QD emission. (c) The estimation of QD and cavity line-width by observing the cavity and QD emission respectively. This shows that this coupling can be used for resonant QD spectroscopy.

References:

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